# Low Temperature Characterization of Mechanical Isolators for Cryocoolers

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## ABSTRACT

For spacecraft applications requiring active refrigeration, exported vibrations from a cryocooler can be a concern. One approach to minimizing the vibrations transmitted from cryocoolers to the spacecraft is to mount them on mechanical isolators. Many commercial off-the-shelf (COTS) mechanical isolators exist and have been characterized at room temperature for ground applications. However, the space environment presents challenges that complicate the selection process. Mechanical isolators in space must be made of materials that can withstand harsh radiation environments. Future instruments, such as the Mapping Imaging Spectrometer for Europa (MISE) on the Europa Clipper mission, are considering operating cryocoolers with low heat rejection temperatures and mounting them on mechanical isolators. However, the performance of many simple, traditional mechanical isolators at low temperatures is unknown. This paper describes the testing and results of various mechanical isolators able to withstand harsh radiation between 200 K and 300 K. The transmissibility of wire rope type isolators showed very little temperature dependence up to ~500 Hz. On the other hand, the transmissibility of silicone gel was strongly dependent on temperature as the material had an abrupt change in stiffness near its solid-solid phase change. Custom titanium flexures showed the most promise with a maximum transmissibility of 0.04 above 500 Hz and no expected temperature dependence.

## INTRODUCTION

The vibration isolation of mechanical cryocoolers from spacecraft can be necessary to mitigate the disturbances imparted on delicate science measurements elsewhere onboard. Vibration isolation and suppression can be achieved with active and passive methods. Active methods are complex and require feedback control. For opposing piston compressors with large piston axis disturbances, the input voltage signal to one motor can be varied to minimize disturbance in that axis. Low-cost, flight-qualified cooler electronics made by Iris Technologies® have this feature built-in and have demonstrated it to be effective [1]. However, this method does not minimize disturbances in the radial piston directions. Active mass dampers can be implemented in these axes further increasing complexity.  On the other hand, passive methods are attractive for their simplicity. Typically, the isolated component is attached to its base structure by means of robust mounts, which have low relative stiffness [2]. However, the potential large relative displacements between the cooler and mounting structure during launch must be considered. Approaches to

(a) (b) (c) (d)

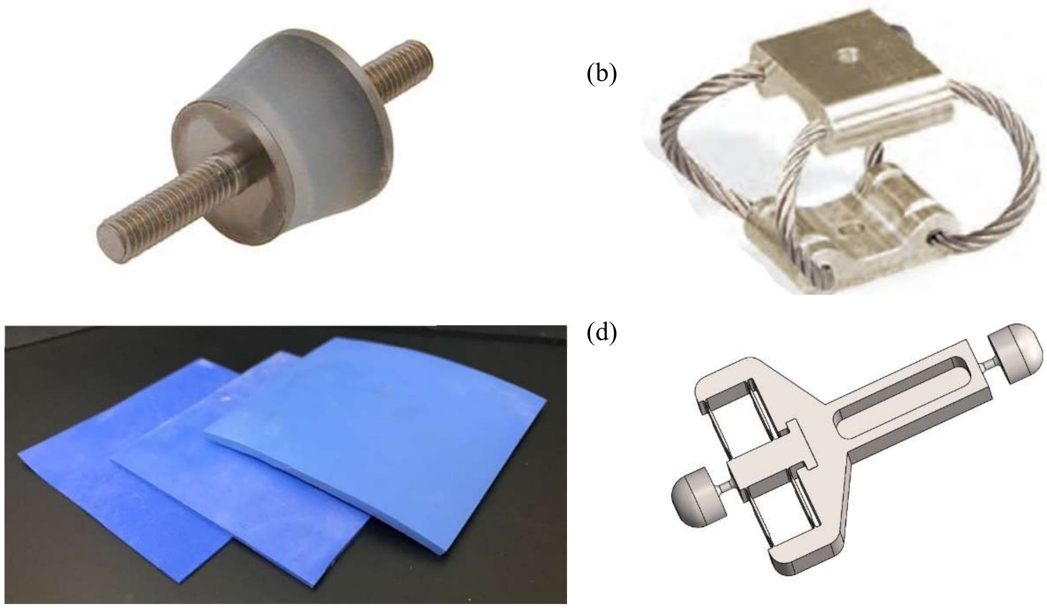

**Figure 1**: (a) Silicone gel isolator, (b) stainless steel wire rope isolator, (c) fluorosilicone rubber sheets, (d) titanium flexures.

accommodating launch loads include designing isolators capable of surviving launch [3] or building bumpers to limit displacement [4]. The stiffness of the mount is selected in order to provide isolation in the frequency range of choice that is driven by the cooler drive frequency. Isolating materials are often rubbers or soft plastics which may not perform well in cold environments and may be degraded by radiation.

The Europa Clipper will orbit Jupiter and image its icy moon during its 45 planned flybys. All materials used in the spacecraft including vibration isolators, must be able to withstand the intense radiation environment of Jupiter and perform at cold operating temperatures. Rubbers and soft plastics are not robust enough to endure this environment, thus new materials need to be explored. The MISE Instrument plans to operate a Lockheed Martin Micro1-2 cryocooler in a 220 K environment [5]. This cooler will operate at 135 Hz and the exported cooler vibrations in the radial direction are on the order of one Newton measured zero-to-peak [1]. The goal of this study was to identify potential candidate isolators that would (i) mitigate disturbances from the MISE cooler, (ii) survive the Europa radiation levels, and (iii) perform appropriately at 220 K.

This paper details the methods and results of testing of four types of isolators, shown in Figure 1 and described in Table 1, which are impervious to radiation: silicone gel, stainless steel wire rope, fluorosilicone rubber and titanium flexures. Two different sizes of Advanced Antivibration Components® silicone gel isolators and two different IIT Enidine® wire rope isolators of different size and stiffness were tested at temperatures ranging from 205 K to 295 K. Three thicknesses of fluorosilicone rubber and custom made titanium flexures were tested at room ambient conditions.

**Table 1**: Overview of isolaors/materials tested.

| **Isolator Type** | **Manufacturer /Model Number** |
|---|---|
| Large Silicone Gel | Advanced Antivibration Components / V10Z61MTHB |
| Small Silicone Gel | Advanced Antivibration Components / V10Z61MTHC |
| Large Wire Rope | IIT Endine / CR2-100-D |
| Small Wire Rope | IIT Endine / CR3-400-D |
| Fluorosilicone Sheets | AAA-Acme Rubber Co. / (various thicknesses) |
| JPL Custom Designed Titanium Flexures | All Tech Precision |

## METHODS

The silicone, wire rope, and fluorosilicone rubber were tested in an ad-hoc cubic vacuum chamber. Figure 2 depicts the test setup and Figure 3 shows a close-up picture of wire rope isolators before testing. A Labworks® shaker, excited by a sine wave output from a Chroma® programmable AC source, was attached to a suspended baseplate through a PCB® 208B force sensor. Four elastic cables allowed the baseplate to float so that the isolators experienced the majority of the input force. Three G10 standoffs held the isolators, which supported a 1.079 kg copper puck. Three single-axis Kistler® accelerometers were aligned with the X, Y, and Z-axes on the base plate and a Kistler® cryogenic accelerometer was aligned with the Z-axis on the copper puck. A black-painted copper shield was attached to the second stage of a CTI Cryogenics Cryodyne® 1050C cryocooler and radiativley cooled the puck and isolators. For all analysis, the isolators were assumed to be at the same temperature as the copper puck.

Cooling the isolators was done radiatively over the period of ~48 hours. Once below 205 K, the cryocooler was turned off and the temperature of the shroud and isolators was allowed to drift upwards. At specified increments, a LabVIEW® program was initiated that collected accelerometer data and automatically ramped the frequency output of the shaker. The voltage output of the AC source was kept constant during each data collection, and the frequency was swept from 31.25 Hz to 1000 Hz at a rate of one octave per minute. The sampling rate was set to 2.5 kHz for all measurements.

Data processing consisted of converting the raw voltage data to acceleration or force and applying a fast Fourier transform to the recorded time domain data of each accelerometer and force sensor. Then the transmissibility was computed. It was defined as the ratio of output acceleration power spectrum to input acceleration power spectrum. A moving average window of 2500 samples was applied to this ratio and peaks due to electoral noise were removed using a custom Matlab® filter.

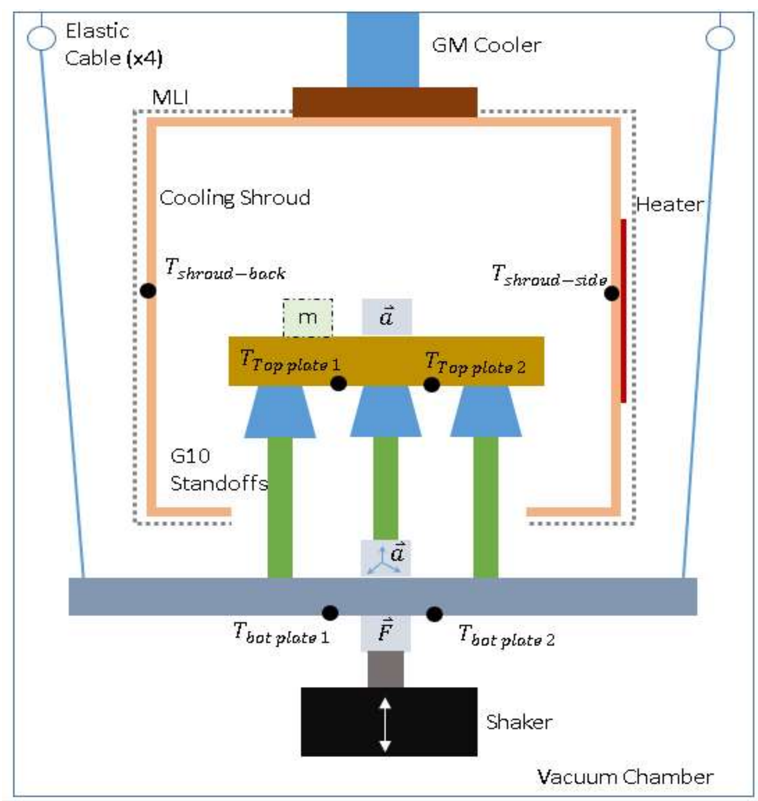


**Figure 2**: Diagram of test setup in chamber showing locations of thermometers and sensors.

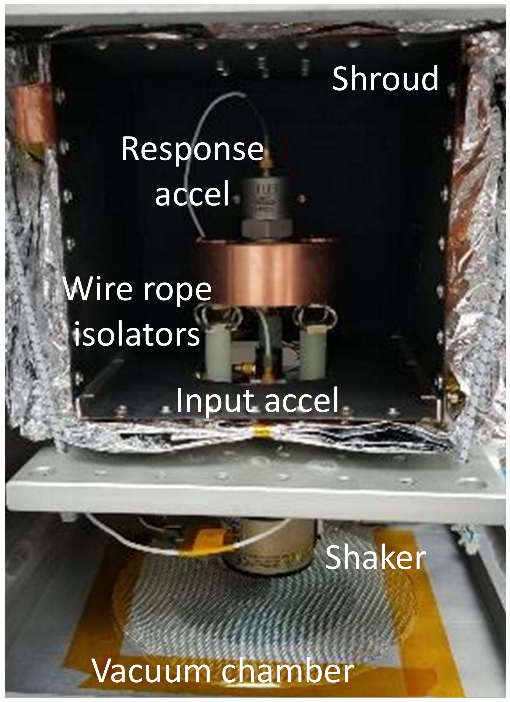


**Figure 3:** Close-up of vacuum chamber.

## RESULTS AND DISCUSSION

### Silicone Gel Isolators

Figure 4 shows the transmissibility as a function of frequency for various temperatures of two sizes of silicone gel isolators. Both isolators demonstrated similar trends as a function of temperature; the transmissibly of each isolator was poor or non-existent at low temperature, but improved as the temperature increased. A transition from non-isolating to isolating behavior occurs between 220 K and 230K as the material passed its melting temperature. Figure 5 shows the modulus of rigidity of silicone rubber as a function of temperature. It shows that silicone undergoes a solid-solid phase change and “melts” beginning at approximately 215 K. The material completes its transition near 240 K [6]. This process causes the material to transition from complexly rigid to flexible, hence the intermediate behavior in this temperature range

At warmer temperatures, the isolating behavior of the silicone gel increases as it approaches a minimum transmissibility of 0.01 near 500 Hz. The isolators again reach their maximum potential near 1000 Hz. At low temperature, some amplification of input is observed above the break frequency making these isolators ineffective below their melting temperature.

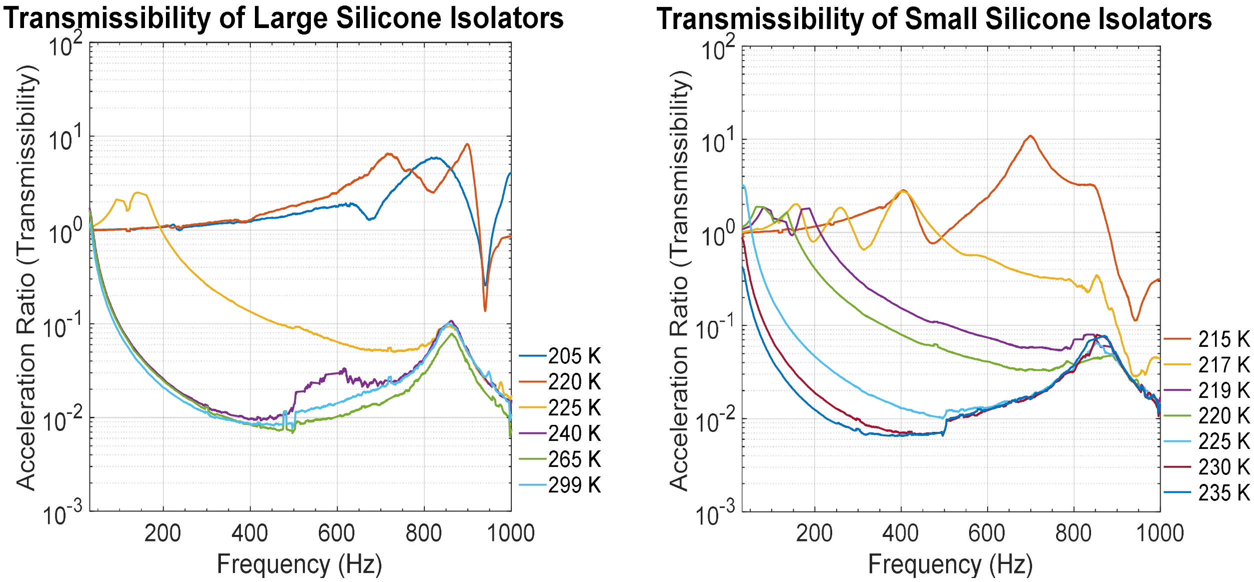


**Figure 4:** Transmissibly plots for silicone isolators.

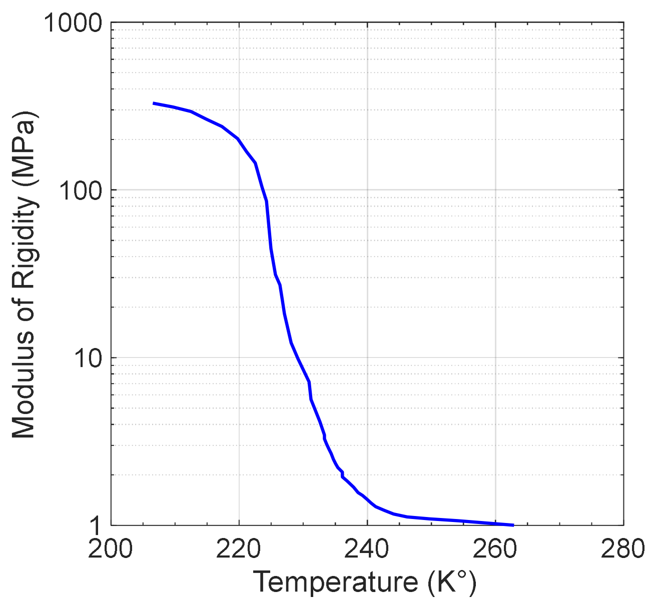


**Figure 5:** Modulus of rigidity of silicone rubber vs. temperature [2].

## Wire Rope Isolators

Isolators that can perform effectively with no dependence on temperature are desired. Wire rope isolators damp vibration through the rubbing and sliding friction between their multiple twisted stainless steel cables. Vibrational energy is dissipated as heat as adjacent cables move relative to each other [7]. Two different types of wire rope isolators of different stiffness and size were tested and showed very similar results to one another. Figure 6a shows the results of a frequency sweep up to 400 Hz for the CR2-100 isolators. These isolators show a resonance point near 100 Hz where input amplification of 10x occurs. The isolators do not exhibit a strong temperature dependence at lower frequencies and the transmissibility begins to decrease past the break frequency. Past 400 Hz a property of the test setup causes the transmissibility to deviate significantly from the expected trend. This deviation could be due to a resonance of the G10 isolators. Looking at the data for the silicone isolators it is obvious that there is a resonance near 850 Hz which is most likely a system resonance rather than a property of the isolators. It has proven to be difficult to design a test setup that is both thermally isolating and rigid at higher frequencies. The same phenomenon is present in the data for the CR3-400 wire rope isolators past 200 Hz.

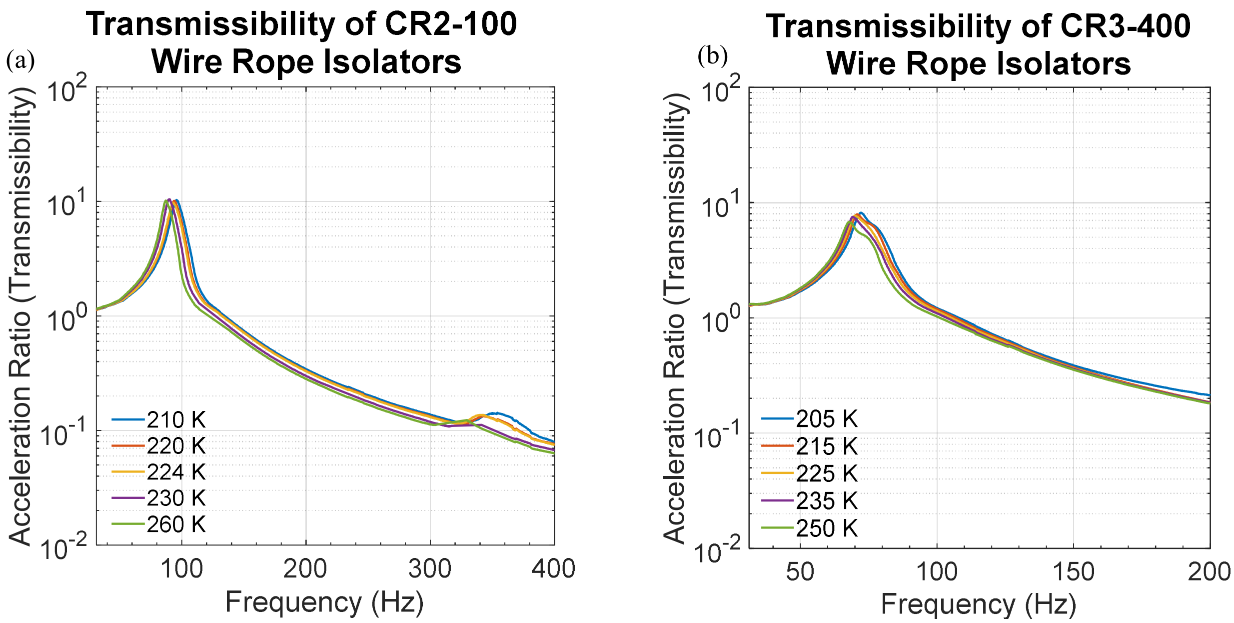


**Figure 6**: Transmissibility of wire rope isolators over frequency sweep.

To investigate this resonance theory further, the CR2-100 isolators were tested parametrically with added mass and various input voltages. For simplicity, this test was done at room ambient conditions. Two different masses, 182 grams and 200 grams, were added to the 1072 gram copper puck at constant input accelerations. The RMS acceleration and the isolating mass is indicated on each plot in Figure 7.

The system resonance near 850 Hz can be seen for each case. Adding mass to the copper puck caused the response of the isolators to vary minimally. A slight shift in the first resonance frequency and some various effects at higher frequencies are observed. The input acceleration was increased twice causing the maximum damping frequency to shift slightly upwards each time. This shift casues the width of the second resonance peak to shrink. Figure 8 shows the results of adding mass to the base plate while keeping the isolating mass constant. Overall, adding mass and varying input acceleration has a marginal effect on the performance of these isolators, however the second resonance peak is reduced when adding mass.

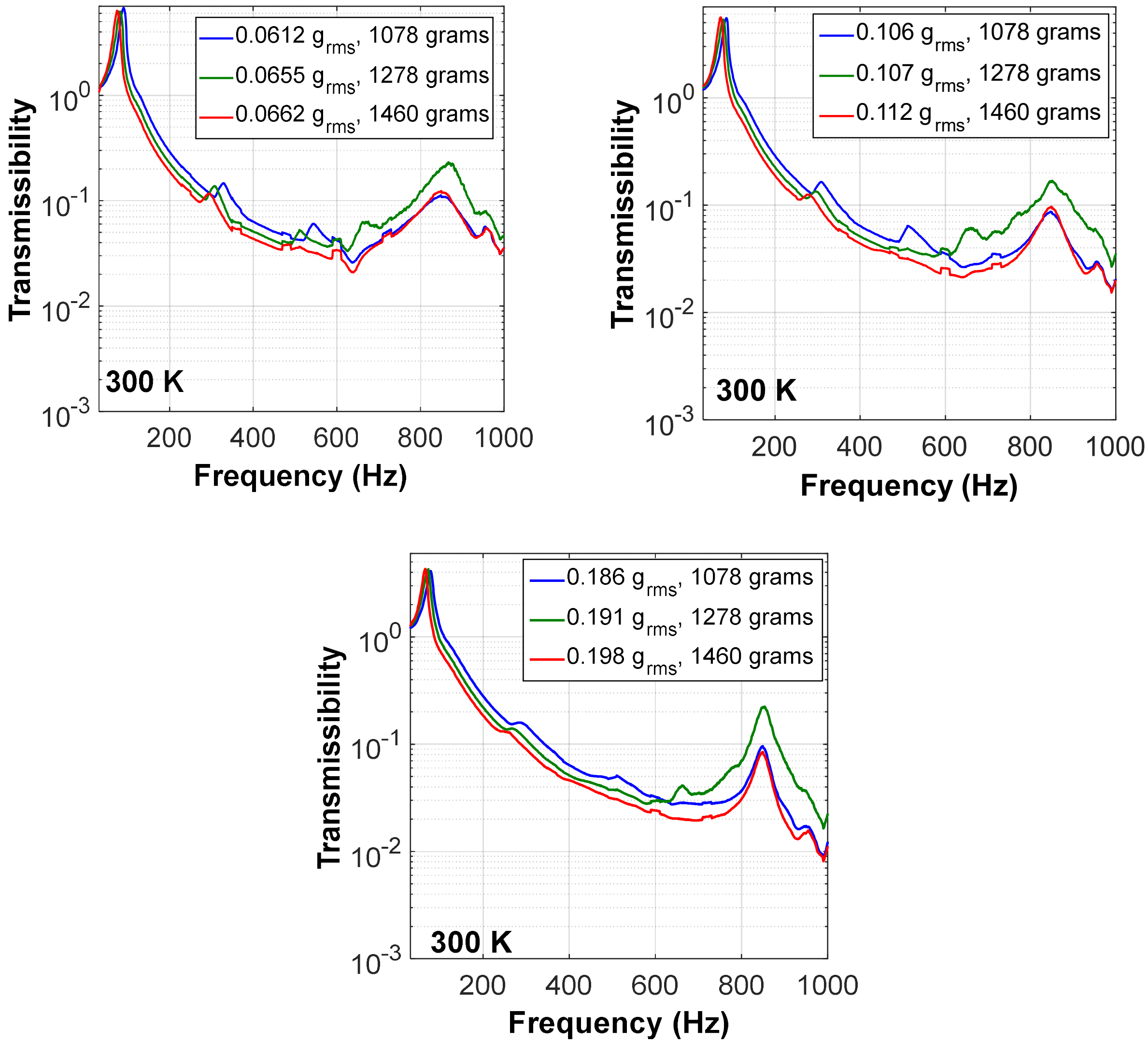


**Figure 7**: Results of parametric study measuring the effect of mass and input acceleration on CR2-100 wire rope isolator performance.

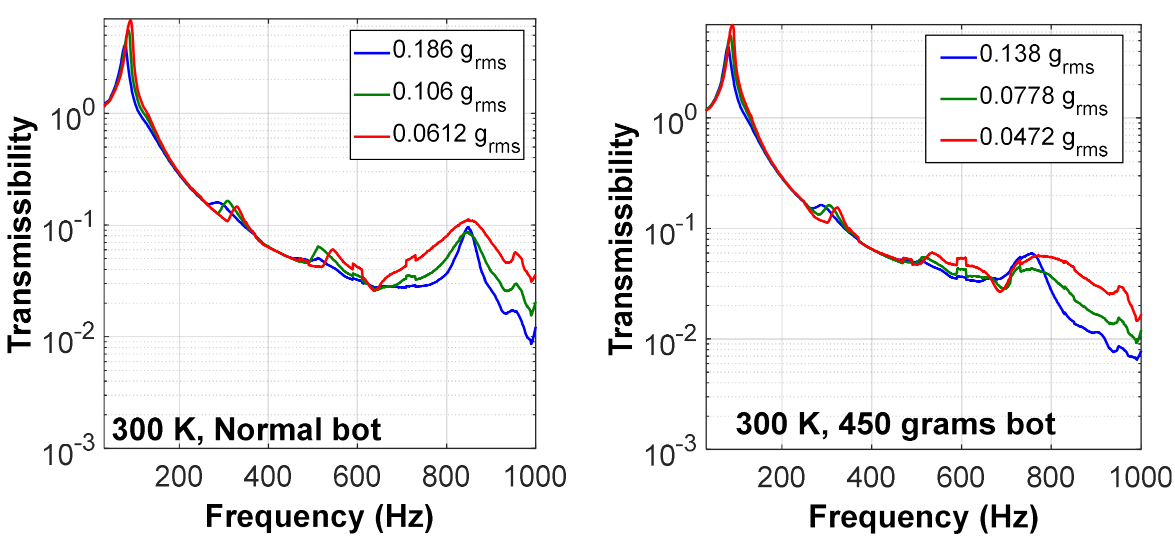


**Figure 8**: Results showing the effect of adding mass to the base plate.

**Fluorosilicone Rubber**

Sheets of fluorosilicone rubber were tested at ambient temperature and pressure to determine the materials isolating potential. 0.032", 0.093", 0.250" thick samples were placed under the copper puck as shown in Figure 10a and the input frequency was swept as in all other tests. While the 0.250" sheet performed marginally better that the other thicknesses, there is minimal isolation in general. A minimum of 0.015 transmissibility is observed near 950 Hz as shown in Figure 10b. The system resonance of 850 Hz is observed again.

(a) (b)

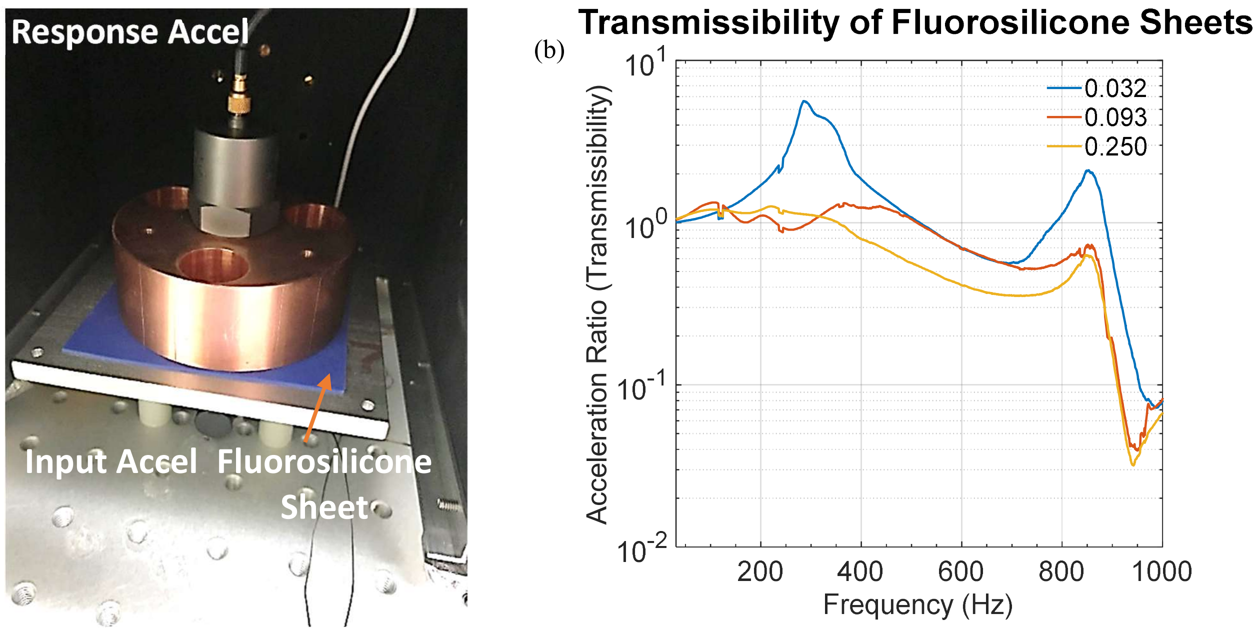


**Figure 9**: (a) Fluorosilicone rubber sheet under copper mass. (b) Transmissibility of three thicknesses of fluorosilicone rubber.

**Titanium Flexures**

Since the results of COTS isolators were not promising, custom flexures made of titanium 6-4, illustrated in Figure 1d, were designed. The flexures were designed with a hard stop to disable launch loads from affecting the cryocooler. Furthermore, they are intended to provide an order of magnitude force reduction at the cryocoolers operating frequency (135 Hz). A hexapod design is used to achieve a kinematic mount for the cryocooler bracket. However, for testing, a configuration with three isolators and half the in-flight mass was used. Finally, the projected vectors of the three isolators meet at the center of mass of the entire assembly as shown in Figure 10b.

Three test isolators were built without the hard stop for simplicity. These three isolators were tested in the configuration shown in Figure 10a. The Labworks® shaker was connected to an upper plate through a force sensor. The three flexures connected to a base plate which was attached to a 3-axis Kistler® dynamometer described in further detail in [8]. At three constant input forces between 0.57 and 1.27 $N_{rms}$ the input frequency was swept as described in the methods section of this paper. The flexures show independence of input force in this range and reached a minimum force transmissibility of 0.04 near 500 Hz. Figure 11 shows the results of a frequency sweep at room temperature with an input force of 0.57 $N_{rms}$.

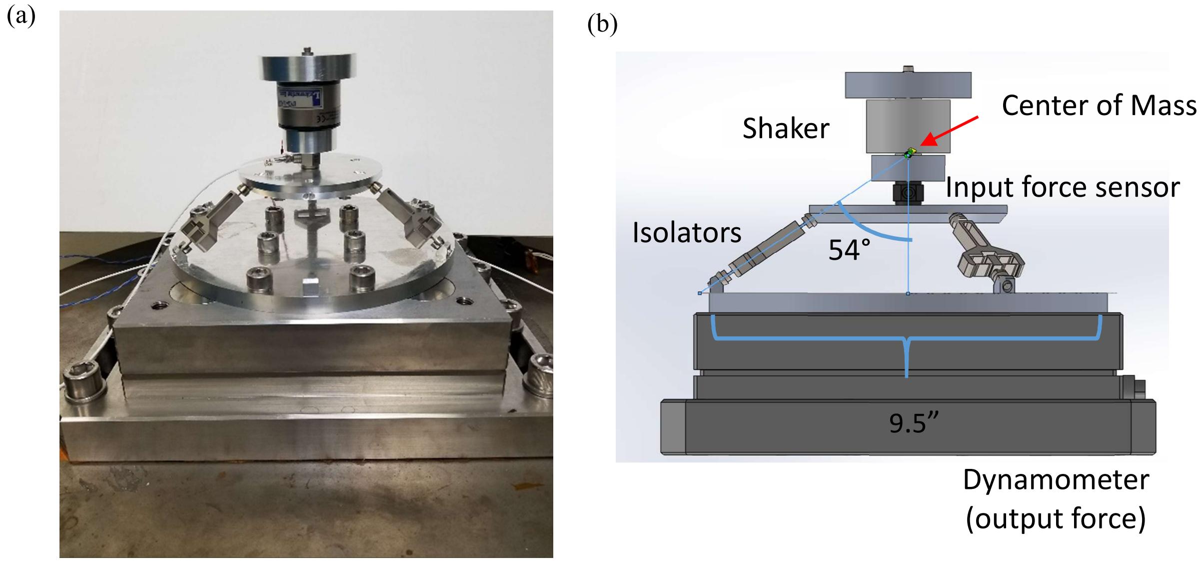


**Figure 10**: (a) Titanium flexures installed on dynamometer. (b) Test layout showing isolator angles all meet at CM of entire assembly.

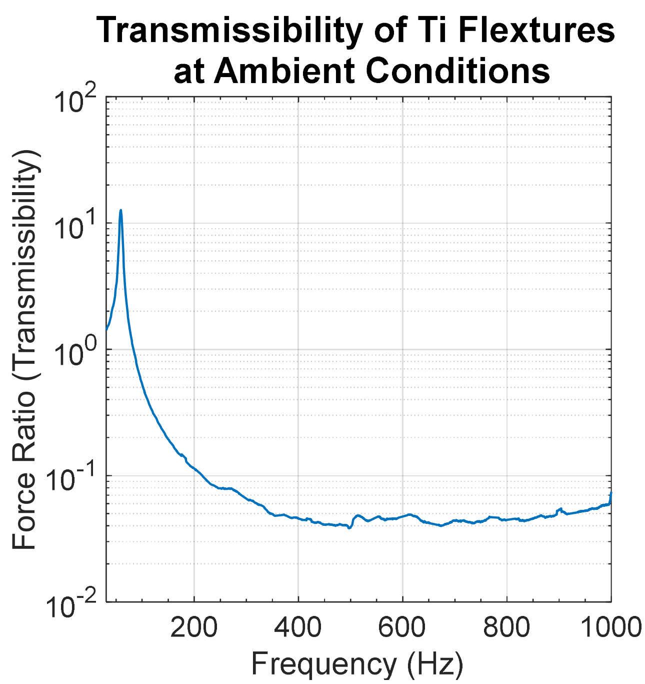


**Figure 11**: Transmissibility of Ti Flexures over frequency sweep at ambient conditions.

## CONCLUSION

This paper described the testing and results of various mechanical isolators and materials able to withstand harsh radiation. Silicone gel isolators were tested between 205 K and 295 K and show significant temperature dependence near their melting temperature. Wire rope isolators were tested in this same temperature range and show no temperature dependence at low frequency and inexplicable behavior at higher frequencies due to a system resonance. Fluorosilicone rubber sheets are poor at isolating vibrations and custom titanium flexures show the most promise with a maximum transmissibility of 0.04 above 500 Hz and no expected temperature dependence.

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## REFERENCES

[1] I. McKinley, C. Hummel, D. Johnson and J. Rodriguez, "Characterization testing of Lockheed Martin high-power micro pulse tube cryocooler," in *Cryogenic Engineering Conference*, Madison, 2017.

[2] Shin-Etrsu Silicone, "Characteristic Properties of Silicone Rubber Compounds," August 2016. [Online]. [Accessed 2018].

[3] P. G. Ramsey, "Development of a Turn Key Cryogenic Cooling Module for Space Flight Based on a Commercial Cryocooler," in *47th International Conference on Environmental Systems*, Charleston, SC, 2017.

[4] H.-U. Oh, K.-J. Lee and M.-S. Jo, "A passive launch and on-orbit vibration isolation system for the spaceborne cryocooler," *Aerospace Science and Technology,* vol. 28, no. 1, pp. 324-331, July 2013.

[5] I. M. McKinley, M. A. Mok, D. L. Johnson and J. I. Rodriguez, "Characterization Testing of Lockheed Martin Micro1-2 Cryocoolers Optimized for 220 K Environment," in *20th International Crycooler Conference*, Burlington, VT, 2018.

[6] C. D. Johnson, P. S. Wilke and S. C. Pendleton, "SoftRide Vibration and Shock Isolation Systems that Protect Spacecraft from Launch Dynamic Environments," in *38th Aerospace Mechanisms Symposium*, Hampton, VA, 2006.

[7] M. L. Tinker and M. A. Cutchins, "Damping phenomena in a wire rope vibration isolation system," *Journal of Sound and Vibration Isolation System,* vol. 157, no. 1, pp. 7-18, 1992.

[8] D. L. Johnson, I. M. McKinley and J. I. Rodriguez, "Flight Qualification Testing of the Thales LPT9510 Pulse Tube Cryocooler," in *Cryocoolers*, Boulder, 2014.